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NACA Research on Hydrogen for High-Altitude Aircraft

Hydrogen was considered as an aviation fuel by P. Meyer in 1918 (p. 12); Tsiolkovskiy considered and rejected it for a rocket-powered airplane in 1935 (p. 256). In 1939, George W. Lewis, director of research for the National Advisory Committee for Aeronautics (NACA) was talking about using liquid hydrogen with atmospheric air, presumably for aircraft propulsion (p. 73). During World War II, F. Simon, a respected physicist in England, nearly confounded the practical fuel experts in the United States by suggesting that liquid hydrogen be used to increase aircraft range (pp. 11–12). Opie Chenoweth, Robert Kerley, John Duckworth, and their associates at Wright Field's power plant laboratory contracted with Ohio State University in 1945 to investigate the application of liquid hydrogen to aircraft and rockets (p. 18). None of these, however, got very far, principally because hydrogen's very low density made its application in volume-limited airplanes appear totally impractical. If this was not enough, opponents to hydrogen clinched their case by citing its very low availability as a liquid and its handling hazards.

Beginning in the 1950s, however, several factors combined to make liquid hydrogen appear exceedingly attractive as an aviation fuel. Among them: incentives to operate airplanes at very high altitudes, advances in liquid-hydrogen technology, and experiments showing that hydrogen burned readily at low pressures.

One of the places where an intense interest in hydrogen for aircraft developed during the 1950s was the NACA Lewis Flight Propulsion Laboratory in Cleveland, where it was pushed hard by the associate director, Abe Silverstein. NACA involvement with hydrogen for this application, however, had its roots in earlier work in fuels and combustion.

One of the initial facilities built at the NACA Cleveland laboratory in the early 1940s was a well equipped chemical laboratory for fuels and lubricants. New fuels or blends for piston engines could be synthesized, and during the war, for example, the laboratory studied alternate high-octane fuels such as the aromatic amines. With the switch from piston to jet engines after the war, the type and characteristics of desired fuels also shifted. The amount of heat obtainable per unit mass and volume became of great importance. Research involved not only the theoretical energy content of fuels, but how to release and harness that energy over a range of operating conditions. How

well did the fuel mix in an air stream? Would the fuel ignite and propagate over a range of combustible mixtures? How efficient was the combustion process over a range of operating conditions, particularly at the reduced pressures of high altitude? Such questions became important for research to answer.

In 1948, the Lewis laboratory presented its research on fuels at a conference; six of the nine papers were on fuels for turbojets and ramjets.[1] Melvin Gerstein discussed powdered metallic fuels such as aluminum and beryllium, which had heats of combustion per unit volume up to four times greater than gasoline. Gerstein also discussed diborane, reporting that its flame speed was fifty times greater than that of hydrocarbons. It was part of the great love affair with diborane and pentaborane by the laboratory and others which extended beyond the mid-1950s.

In 1950, the uneasy international situation, and especially the outbreak of the Korean war, led to an acceleration of aeronautical research and development. One goal was aircraft capable of operating at very high altitudes, and one obstacle in doing this was described by Walter T. Olson, J. Howard Childs, and Edmund R. Jonash of the Lewis laboratory in 1950:

> Experience has shown that, as operating altitudes are progressively increased beyond 25000 feet [7600 m], the effects of altitude on combustion efficiency ultimately result in severe penalties in thrust and specific fuel consumption. The problem of maintaining high combustion efficiency is one of the most important problems of altitude operation.[2]

The investigators found that combustion efficiency increased with fuel volatility, with greater hydrocarbon content as compared to aromatics, and with more straight-chain and fewer branched-chain hydrocarbons.

The following year, Olson and Louis Gibbons surveyed fuels suitable for ramjets and summarized results achieved by several organizations, including the experiments on liquid hydrogen at Ohio State University. Although Olson and Gibbons included liquid hydrogen among the fuels of interest, they were more interested in investigating diborane, pentaborane, and slurries of magnesium and aluminum.[3] The same year, Benson E. Gammon examined the performance of liquid hydrogen and two other fuels for ramjets, finding hydrogen superior per unit mass but inferior per unit volume.[4] Another Lewis laboratory analyst, Hugh M. Henneberry, considered fuels for aircraft during 1951 and concluded that:

> neither the very high nor very low fuel densities have any advantage for long-range flight . . . the practical difficulties associated with the use of liquid hydrogen cannot be justified on a range basis, but *if tactical considerations predicate flight at extremely high altitudes, liquid hydrogen must be considered as a possible fuel* [emphasis added].[5]

There it was—the advantage of hydrogen for attaining extremely high altitudes—but Henneberry, like others at Lewis, was impressed by the potential of another high-energy fuel, diborane, and consideration of hydrogen went no further at that time.*

*For flight at an altitude of 21 000 m and speed of Mach 3.6. Henneberry concluded that diborane had a 59 percent greater range than hydrocarbon fuels.

The military services and their advisors also showed little or no interest in hydrogen for aircraft prior to 1954. The Navy had embarked on a massive investigation of boron-hydride fuels for jet engines and was joined in this effort by the Air Force and NACA.[6] The fuels and propulsion panel of the USAF Scientific Advisory Board, in considering high-energy fuels at its April 1952 meeting,* noted that rockets favored fuels with combustion products of minimum molecular mass but that "this condition is irrelevant in a turbojet."[7] This indifferent attitude towards hydrogen appeared to prevail generally for two more years until a series of events, starting in 1954, swept it aside like fog before the wind.

New Interest in Hydrogen

Beginning in February 1954 and extending through March, the fuels and propulsion panel of the Scientific Advisory Board met three times, in an exhaustive survey of the major aspects of the propulsion program of the Air Force.[8] Although no mention was made of hydrogen in the minutes, the panel was greatly interested in high-energy fuels and the Air Force program on them. On the same day as the last meeting (24 March 1954), Randolph S. Rae visited Wright Field with a proposal to use hydrogen in a high-altitude aircraft powered by a unique engine called Rex I. By all indications his visit touched off a strong renewal of interest in liquid hydrogen for aircraft, which will be described in the following chapter.

The origin of interest within NACA to use hydrogen as an aviation fuel has not been fully established, but experiments began in 1954. Several events apparently contributed to the NACA interest. In Washington, A. M. Rothrock, chief of propulsion research, completed a comprehensive survey and analysis of turbojet propulsion and its effect on airplane performance in August; it was published seven months later. Rothrock discussed seven major propulsion factors and the state-of-the-art concerning them. One was the heat of combustion of the fuel—where, of course, hydrogen excels. Rothrock's favorite way of beginning such a discussion was to show a plot of heat of combustion as a function of atomic number, and hydrogen was higher than the upper limit of his scale. Despite this, Rothrock's discussion of hydrogen revolved more around hydrogen as an element in fuel molecules than as a fuel per se. He acknowledged interest in hydrogen mainly in focusing on the current favorite fuels, the boron hydrides, and did not mention hydrogen in his conclusions. A month after completing his report, Rothrock attended a meeting of the fuels and propulsion panel of the Scientific Advisory Board when Rae's Rex engine using hydrogen was discussed.[9] Apparently Rothrock was not sufficiently impressed with the idea of using low-density hydrogen in volume-limited aircraft to change his report, which was still in the process of publication; but he may have passed word on the hydrogen proposal to the Lewis laboratory.

In 1954, current turbojet engines could operate at altitudes of 13 700 meters without serious loss of combustion efficiency. Under the direction of Olson and Childs, a group

*The chairman was Prof. C. Richard Soderberg, M.I.T. Other members: Louis G. Dunn, William M. Holladay, Andrew Kaletensky, and W. D. Rannie. A. M. Rothrock of NACA attended the meeting as a guest and was later a member, 1953–1955.

of researchers at the Lewis laboratory was engaged in a series of experiments to relate the effect of fuel characteristics, combustor design, and altitude operation on combustion efficiency. From this research, the altitude limits for good combustion had been extended to 21 000 meters, but the goal was 30 500 meters. As part of this research, Jonash, Arthur Smith, and Vincent Hlavin turned to gaseous hydrogen in 1954 and were not disappointed.* In their report completed two days before Christmas, 1954 (published five months later), they indicated that hydrogen burned well in a single turbojet combustor at pressures as low as 1/10 atmosphere; at 1/4 atmosphere, combustion efficiency was above 90 percent. These results were within the combustion pressure range for turbojet engines operating at 30 500 meters altitude. The authors believed that they could attain 100 percent combustion efficiency with better mixing of hydrogen and air. Propane was investigated briefly and found to be greatly inferior to hydrogen, with the difference attributed to hydrogen's higher flame speed and wider flammability limits.[10]

Sometime during 1954 or early 1955, Abe Silverstein, the associate director of the Lewis laboratory, was struck with an idea concerning hydrogen. Well aware of high-altitude flight objectives and well versed in aircraft design principles, he suddenly saw a way of using hydrogen's superior combustion characteristics and coping with its principal disadvantage, low density. At high altitudes and low speeds, large wings are needed and these call for a proportionately large fuselage. Under these flight conditions, the drag of the airframe is low. The large volumes available in the wings and fuselage favored the use of low-density liquid hydrogen, provided lightweight hydrogen tanks proved feasible.

As was his custom when struck with a new idea, Silverstein made some approximate or "back of the envelope" calculations. He became so enthused over the results that he went to Washington to discuss them with Hugh Dryden, NACA director of research. Dryden, too, was impressed, and the two discussed the idea with Air Force officials. Silverstein was convinced that he had something good, but needed more detailed calculations to back it up.[11]

Silverstein-Hall Report

When Silverstein returned from Washington, he asked Eldon Hall, one of the laboratory's top analysts, to assist him in refining his analysis on using hydrogen for high-altitude aircraft. While this was under way, the fuels and propulsion panel met in March 1955 to discuss high-energy fuels.† The panel was very impressed with the potential of liquid hydrogen and boron hydrides.[12] The work of Jonash, Smith, and Hlavin was described, as well as current work by Thaine W. Reynolds of the Lewis laboratory. Reynolds, who was assisting Hall in the analysis for Silverstein, was studying lightweight tanks for hydrogen and was convinced that they were feasible.

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*Whether the Lewis group thought of using hydrogen independently or as a result of a suggestion by the Air Force or by Rothrock has not been established.

†Mark M. Mills had succeeded Soderberg as chairman. Other members: W. D. Rannie, E. S. Taylor, Gale Young, and A. M. Rothrock.

The fuels and propulsion panel suggested that the Air Force begin work on hydrogen fuel systems, hydrogen-fueled engines, and preliminary designs of hydrogen-carrying aircraft. This meeting apparently spurred the Lewis analysts to faster action, for Silverstein and Hall completed their report on 1 April 1955 and published it two weeks later—a near record for fast NACA publication and an indication of the importance Silverstein attached to the subject.

In their introduction, Silverstein and Hall noted that despite hydrogen's high heating value and good combustion characteristics, it had received only casual attention. They acknowledged the deterrents of low density, low availability, and difficult handling, but made a case for considering hydrogen based on four points: a military need that could not be met in any other way, advantages of hydrogen for high-altitude flight, improvements in jet engines that indicated their mass could be halved for the same power, and large wing and fuselage requirements for high-altitude flight. The first two points were based on hydrogen's unique properties. The third favored light weight, and the fourth high volumes, to overcome hydrogen's disadvantage of low density. As for availability and handling, Silverstein and Hall cited past experiences, implying that if the flight problems could be solved, so could those on the ground.[13]

Of the flight problems, the authors singled out hydrogen tankage as a major problem. They drew on the technology of long-range missiles, particularly the Atlas, and suggested that liquid hydrogen tanks be constructed as cylindrical balloons of light-gage metal, depending upon internal pressure to maintain shape (fig. 19). This, of course, was the same idea proposed by Oberth in the 1920s and Martin and North American engineers in the 1940s, and being used for the first time on the Atlas ICBM amid some skepticism.

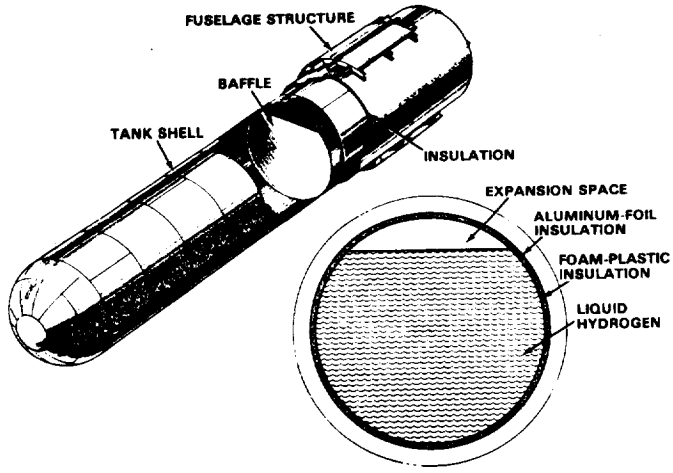

Fig. 19. Liquid-hydrogen tank suitable for aircraft as envisioned by Abe Silverstein and Eldon Hall, "Liquid Hydrogen as a Jet Fuel for High Altitude Aircraft," NACA RM E55C28a, 15 Apr. 1955. Of light-gage metal that depended on internal pressure to maintain its shape, the tank was 25 m long, 3 m in diameter with a volume of 175 m^3. Liquid-hydrogen capacity was 11300 kg. The estimated tank mass was 10 percent of the fuel mass.

Using the basic hydrogen-tank design, Silverstein and Hall analyzed the use of liquid hydrogen for a subsonic bomber, subsonic reconnaissance airplane, and supersonic fighter. Of these, the reconnaissance type will be described as a typical example and for its relationship to later events.

The subsonic reconnaissance airplane had a gross mass of 40000 kilograms and carried hydrogen tanks in wings and fuselage, as well as optional drop tanks for additional range (fig. 20). It operated at an altitude of 24000 meters and could make observations 13500 kilometers from its base. A supersonic version was about 1/4 lighter, operated at the same altitude at a speed 3 times faster, but had a range less than 1/5 the subsonic type.

The subsonic version was powered by advanced turbojet engines weighing about half those in current use. The supersonic type also used an advanced turbojet that was equipped with an afterburner. Additional data on the airplanes and engines are given in table 2.

Silverstein and Hall concluded that "within the state of the art and the progress anticipated, aircraft designed for liquid-hydrogen fuel may perform several important missions that comparable aircraft using hydrocarbon (JP-4) fuel cannot accomplish." They also concluded that "substantial applied research and development effort will be required in many technical fields to achieve the goals outlined."[14] It was a convincing case for hydrogen if the assumptions were accepted. Silverstein, as the chief research executive of the Lewis laboratory, thereupon initiated a massive research program on hydrogen to give substance to his assumptions.

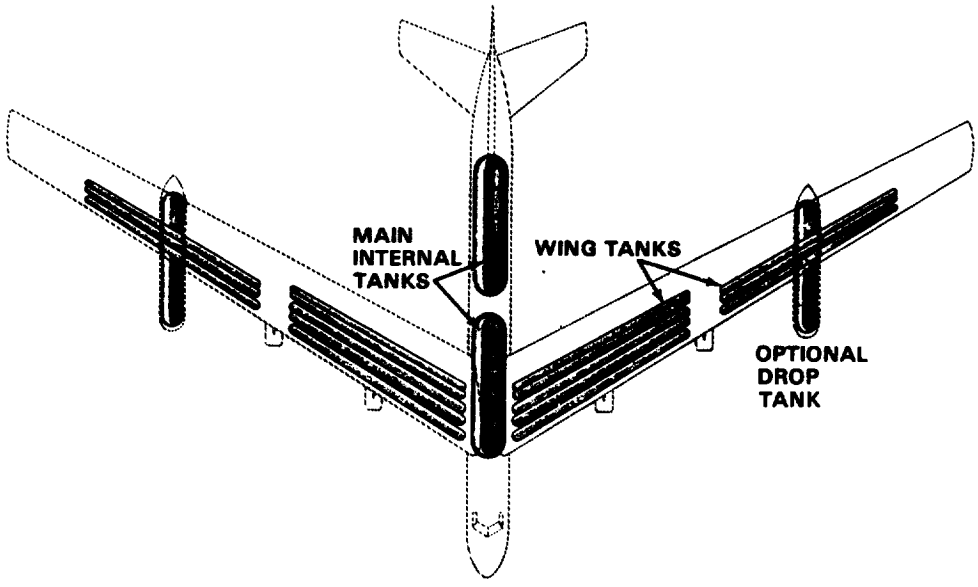

Fig. 20. High-altitude, subsonic reconnaissance airplane using liquid hydrogen as fuel. The liquid hydrogen tanks are in both fuselage and wings. Flight Mach number, 0.75; altitude 24400 m. From Silverstein and Hall, "Liquid Hydrogen as a Jet Fuel," 1955.

TABLE 2.--*Characteristics and Performance of Reconnaissance Airplane and Engine Designs*

Item	Reconnaissance Airplane	
	Subsonic	Supersonic
Cruise Mach No	0.75	2.5
Cruise altitude, m	20000	22000
Target altitude, m	24000	24000
Gross mass, kg	39800	34000
Fixed (instruments, cameras, controls)	2268	2268
Structures	13000	13000
Engine	6328	6169
Fuel tank	2372	1610
Fuel	15760	10730
Wing		
Area, m^2	348	107
Sweep angle, deg	31	0
Aspect ratio	13	3
Average section thickness ratio	0.12	0.03
Taper ratio	2	2
Empennage area, m^2	87	32
Fuselage		
Length, m	45	52
Diameter, m	3.5	3.7
Lift coefficient, initial cruise	0.54	0.14
Lift/drag ratio (airplane less engine nacelles, initial cruise)	25.4	4.33
Radius, km	13500	2490
Engines (turbojet)		
Number	4	4
Compressor diameter, m	0.87	0.84
Sea-level thrust N	64050	72500
(lb)	(14400)	(16300)
Cruise specific fuel consumption, kg/hr/N	0.040	0.072

From Abe Silverstein and Eldon Hall, "Liquid Hydrogen as a Jet Fuel for High-Altitude Aircraft," NACA RM E55C282, 15 Apr. 1955, p. 21.

A key assumption of the Silverstein-Hall analysis was the feasibility of lightweight, insulated flight tanks suitable for liquid hydrogen. Reynolds continued his investigation and reported the results in August 1955. Table 3, taken from the report, summarizes the results. Reynolds concluded that it was feasible to design a tank that had a mass less than 15 percent of the liquid hydrogen it contained. Estimated hydrogen vaporization rates were less than 30 percent of hydrogen consumption during cruise, and prior to flight, the tank could be held in stand-by condition and readied for flight in a short time.[15]

Following the completion of the report with Hall on flying aircraft fueled with hydrogen, Silverstein again visited the Air Force with missionary zeal. He also set in motion a great wave of research related to hydrogen's use in aircraft at the Lewis laboratory. This included properties, combustion, materials, tankage, bearings, pumpings, controls, and complete engines. In 30 months, the investigations led to three dozen reports and were climaxed by a research conference in November 1957.

In September 1955, Jerrold D. Wear and Arthur L. Smith completed an investigation of six types of injectors for burning gaseous hydrogen in a turbojet

TABLE 3.—*Flight-Type Liquid-Hydrogen Tank Design*

Size:		
Diameter, m		3.05
Length, m		24.9
Volume, m^3		174.2[a]
Surface area, m^2		238.2
Working pressure, atm		2
Styrofoam[b] insulation:		
Thickness, cm		5.7
Density, kg/m^3		20.8
Mass of tank:		
Shell, kg		1163
Insulation, kg		284
Covering, kg		29
Allowance for baffles and stiffeners, kg		112
Approximate total mass, kg		1588[c]
Estimated performance with ambient temperature at:	300 K	218 K
Outer surface temperature, K	285	154
Heat-leak rate, W	25770	14500
Hydrogen-vaporization rate, kg/hr	206	116
No-loss time on ground, min	165[d]	

[a] Holds 11340 kg liquid hydrogen with 9 percent expansion volume

[b] Covered with layer of Mylar-aluminum foil.

[c] About 14 percent of fuel mass.

[d] For a tank with 5.7 cm insulation, precooled with liquid nitrogen. No-loss time is the time for heat leaking into the tank to vaporize enough hydrogen to raise the pressure to the working pressure (2 atm).

From: T.W. Reynolds, "Aircraft-Fuel-Tank Design for Liquid Hydrogen," NACA E55F22, 9 Aug. 1955, p. 9.

combustor.[16] They found that at conditions simulating full power, all six injectors gave high combustion efficiency—an indication of the ease of burning hydrogen. Some relatively low combustion efficiencies were obtained, but these were at conditions where ordinary jet fuel would not burn. These experiments were followed by others as the laboratory probed deeper and deeper into the combustion of hydrogen under a variety of conditions.

Bee Project

The component and engine testing of hydrogen in the laboratory, essential as they were, did not answer an important question: Was it practical to use liquid hydrogen in an aircraft? Silverstein had been interested in finding this out from the beginning and his big opportunity came from a parallel interest by the Air Force.

In the fall of 1955, the power plant laboratory of Wright Field, headed by Col. Norman C. Appold, planned an experiment to determine the feasibility of flying an airplane fueled with liquid hydrogen. The bids for a contract—about $4 million a year for 3 years—were higher and longer than anticipated. Lt. Col. Harold Robbins, ARDC headquarters and former Air Force liaison at Lewis, suggested that the NACA be approached to do the work. Silverstein jumped at the opportunity. He promised to do the job in 12 months and with $1 million for special equipment. The agreement was

reached in December 1955, and Silverstein lost no time in getting started. He chose Paul Ordin to be the project manager, assisted by Donald Mulholland. The project staff was quickly selected and put to work on their new assignment.[17]

Although Silverstein was technical head of a laboratory with a complement close to 3000, it was characteristic of him to direct the project personally. He had a room in the basement of the administration building cleared for use by the project group. It was directly below his office and convenient for his close supervision. The project was classified secret and known as Project Bee.

The airplane selected for the project was the B-57B twin-engine bomber powered by Curtiss Wright J-65 turbojet engines. The basic plan was to equip the airplane with a hydrogen fuel system, independent of its regular fuel system, and modify one engine to operate on hydrogen as well as its regular fuel, which was JP-4 (kerosene). The airplane was to take off and climb on its regular fuel. After reaching level flight at about 16400 meters, the fuel on one engine was to be switched from JP-4 to hydrogen. When the hydrogen experiment was complete, the fuel flow would be switched back to JP-4 and the airplane would return to base under its normal operating conditions.

The project team, aided by others in the laboratory, began to design and test the various components for the flight system. A liquid hydrogen tank was designed for mounting beneath the tip of a wing. Two methods for pumping liquid hydrogen were selected. The first was to pressurize the hydrogen tank with helium, a simple and fast method but requiring a fairly heavy tank to withstand the pressure. The second was to employ a liquid-hydrogen pump, but this required time for development. Consequently the first tests were made with the pressurization system.

Earlier combustion experiments showed that gaseous hydrogen burned easily in the turbojet engine. To feed gaseous hydrogen to the airplane engine required some means for gasifying the liquid. A heat exchanger was designed and tested for this purpose. Ram air passed through it during flight to heat and gasify the liquid hydrogen.[18]

The dual fuel system and transition between the two fuels, JP-4 and gaseous hydrogen, called for an integrated control system, the key component of which was a flow regulator for the gaseous hydrogen. The speed of the engine was controlled by coupling the hydrogen flow regulator to the engine's JP-4 fuel control.[19]

The flights were the province of the laboratory's test pilots headed by William V. (Eb) Gough, Jr., the fourth Navy pilot to qualify in helicopters and the thirtieth in jets; he joined the NACA as a test pilot after the war. By early May, Gough had checked out on the B-57 at the Glenn L. Martin plant in Baltimore and the Air Force had ferried a B-57 to Cleveland for the experiments.[20]

Assisting Gough was Joseph S. Algranti, another test pilot, who would fly in the rear seat and operate the special controls of the hydrogen fuel system. He participated in the ground testing of the system from the beginning of the project. A third test pilot served as back-up and was in charge of the ground control station.

The testing of the flight components required a considerable amount of liquid hydrogen—the problem that had plagued the rocket group at Lewis for a long time. The Air Force made available mobile hydrogen liquefaction equipment and tanks from the hydrogen bomb program. Glenn Hennings got the equipment in good working order and was soon producing liquid hydrogen for the various laboratory needs.[21] In the first half of 1956, as part of another program, the Air Force let a contract

to build at Painesville, Ohio, a hydrogen liquefaction plant with a capacity of 680 kilograms per day. When this plant began production late in 1956, it supplied all of Lewis's hydrogen needs.

Concurrent with the development of the flight system for supply and controlling hydrogen to the engine, a number of experiments were conducted with single turbojet combustors and full-scale engines using gaseous hydrogen as a fuel. The engine performance was high and insensitive to initial hydrogen temperature.[22]

In other research, hydrogen in a combustor 2/3 as long as a standard one, outperformed JP-4 and also operated at an altitude of 26000 meters—6000 higher than the limit for JP-4.[23] This meant that a shorter engine was possible with hydrogen, with accompanying substantial savings in mass. In another investigation, a team led by William A. Fleming compared the altitude performance of two turbojet engines, one burning hydrogen and the other JP-4. The engines were single-spool, axial-flow types, developing 33–45 kilonewtons (7500–10000 lb thrust). Hydrogen provided stable operation to the limits of the test facility—about 27400 meters and Mach 0.8. In comparison, the same engine using JP-4 flamed out at altitudes 3000 to 4500 meters lower. Further, the specific fuel consumption (mass flow of fuel per hour divided by thrust) of hydrogen was 40 percent that of JP-4 fuel.[24]

Silverstein wanted a thorough check of the engine and control system, using both JP-4 and hydrogen fuels in the altitude wind tunnel before attempting flight. This was carried out by Harold R. Kaufman and associates, including test pilot Algranti. The hydrogen system consisted of a stainless steel, wing-tip fuel tank, a heat exchanger that utilized air passing through it to vaporize the liquid hydrogen, and a regulator to control the flow of hydrogen to the engine. The J-65 turbojet engine was modified by the addition of a hydrogen manifold and injection tubes. The modification did not change the engine's regular fuel system using JP-4. Kaufman reported that with JP-4 the maximum altitude for stable combustion was about 20000 meters and flame-out occurred at 23000 meters. In contrast, hydrogen was stable to the limit of the facility at 27000 meters at flight-rated speed and temperature. The thrust was 2 to 4 percent higher, and specific fuel consumption was 60 to 70 percent lower, than with JP-4 fuel.[25]

In the simulated flight tests, 38 transitions were made from JP-4 fuel to hydrogen. Over three-fourths of these were satisfactory. The others had some engine speed variations, but they were so small and short in duration that the engineers believed there would have been no detrimental effect on aircraft performance. These satisfactory results in the altitude chamber cleared the way for testing the hydrogen system in the B-57.

The hydrogen fuel tank on the left wing of the airplane (figs. 21 and 22) was 6.2 meters long with a volume of 1.7 cubic meters. The stainless steel tank was designed for a pressure of 3.4 atmospheres and insulated by a 5-centimeter coat of plastic foam, covered by aluminum foil and encased in a fiberglass covering. On the opposite wing was the helium supply consisting of 24 fiberglass spheres charged to 200 atmospheres. The helium was used for pressurizing the hydrogen tank and for purging. A heat exchanger for vaporizing the liquid hydrogen, a flow regulator, and a manifold for feeding gaseous hydrogen to the engine comprised the rest of the hydrogen system.

As Christmas neared, pilots Gough and Algranti made a series of checkout flights without hydrogen, and finally the big day came. On 23 December 1956, Scotty

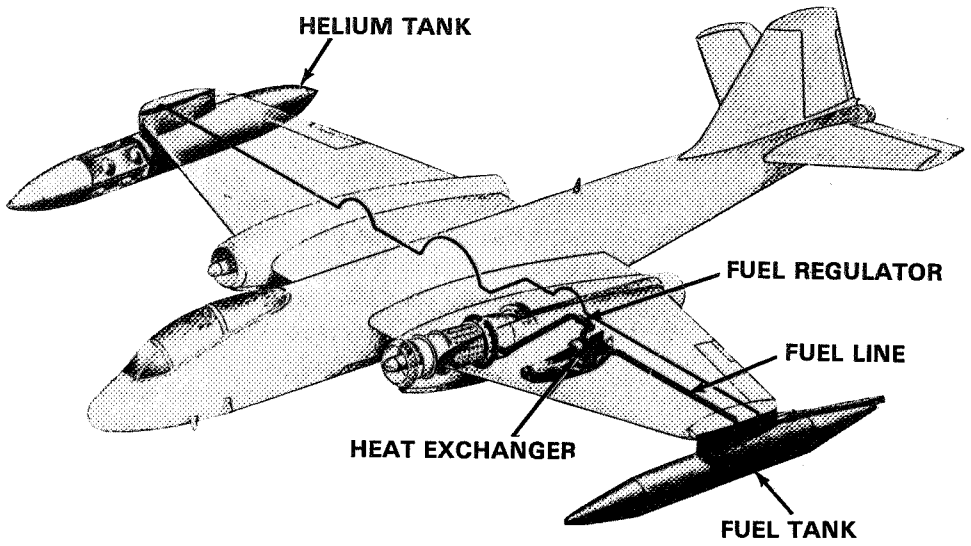

Fig. 21. Liquid-hydrogen fuel system for one engine of a B-57 airplane installed by the NACA Lewis laboratory.

Fig. 22. B-57 airplane modified by the NACA Lewis laboratory to use liquid hydrogen in one engine. The wing-tip pod on the right (the airplane's left wing) is the hydrogen tank; the opposite pod contains helium for pressurization and purge. The dense smoke is normal in starting this engine on conventional fuel.

Simpkinson made the final check of instruments and the B-57 was fueled with JP-4. It was then towed to a remote site for loading liquid hydrogen. The vent of the tank was connected by pipe to a discharge area well away from the airplane and the system purged with helium. After countdown, 94 kilograms of liquid hydrogen were loaded into the wingtip tank. The ground crew left the vent-pipe system connected until Gough started the plane's engines on JP-4. At that time, Algranti closed the vent valve, the ground crew disconnected the vent line, and Gough began to taxi. He was accompanied by an Air Force chase plane equipped with a camera.[26]

As the B-57 taxied into position for take-off, Algranti was maintaining the pressure in the liquid hydrogen tank. With the vent valve closed, the vaporization of a small amount of hydrogen caused the pressure in the gas pocket above the liquid hydrogen to rise. The vaporization was caused by heat leakage through the insulation, which is unavoidable in a practical installation. From ground testing, Algranti knew that the pressure would rise from 1 to 3.5 atmospheres in about five minutes, and he had to manually vent the tank when the pressure began to rise above 3.5 atmospheres. While taxiing, he noticed that the rate of pressure rise was considerably slower than in ground tests; the instrument records indicated that sloshing and agitation of the hydrogen during taxiing slowed the pressure rise by a factor of two. During takeoff, the tank pressure dropped sharply from agitation. Once airborne, however, the agitation ceased and the pressure began to rise at about the same rate as in the stationary tests. This phenomenon was caused by thermal gradients and stratification of liquid hydrogen and its vapor and was the subject of detailed investigation later.

The takeoff and climb to the cruising altitude of 15 200 meters took almost an hour, and during that time, Algranti vented the tank 8 times to keep the pressure within limits. This resulted in a loss of about 16 percent of the hydrogen. On signal, Algranti made the transition from JP-4 to hydrogen. The engine responded by overspeeding and vibrating hard. The startled pilots quickly shut it down, purged the lines, and jettisoned the liquid hydrogen in the wing tank. The B-57 was difficult to fly on one engine, but Gough's training included this contingency. The experiment had taken place over Lake Erie and the weather had deteriorated. Gough dismissed the chase plane, but the pilot elected to accompany him back to the Cleveland airport. The two landed side by side on dual runways in a light rain.

Although the first flight was unsuccessful in operating the engine with hydrogen for an extended period, it was successful in showing that hydrogen could be handled and jettisoned safely. In addition, data were obtained on the phenomenon of hydrogen thermal stratification in the tanks.

The second flight was also only partially successful. The transition from JP-4 to hydrogen was made successfully, but insufficient hydrogen flow prevented satisfactory high-speed engine operation. Again, the bulk of the hydrogen was jettisoned without incident. The jettisoning took less than 3 minutes, with the hydrogen forming a dense plume which vanished about 6 meters aft of the tank.

On 13 February 1957, the first of three successful flights was made and the fuel system worked well.[27] The transition to hydrogen was made in two steps. The hydrogen lines were first purged, then the engine was operated on JP-4 and gaseous hydrogen simultaneously. After two minutes of operations on the mixture, Algranti switched to hydrogen alone. The transition was relatively smooth and there was no appreciable

change in engine speed or tailpipe temperature. The engine ran for about 20 minutes on hydrogen. The pilots found that the engine responded well to throttle changes when using hydrogen. When the supply was almost exhausted, the speed began to drop. As this became apparent, Algranti switched back to JP-4 and the engine accelerated smoothly to its operating speed. The engine burning hydrogen had produced a dense and persistent condensation trail, while the other engine operating on JP-4 left no trail.

On 26 April, Silverstein held a special conference to report what had been learned by the Bee project using hydrogen in flight. The 175 attendees heard 7 papers by 19 members of the project team. They covered hydrogen consumption, fueling problems, airplane tankage, airplane fuel system, and the flight experiments. The results were also given in a series of research reports published later.[28]

The first series of flights of the hydrogen-fueled B-57 was made with a helium pressurization system to force the liquid hydrogen from the wing-tip tank to the engines. This required a fairly heavy tank to withstand the pressure. Later, a liquid-hydrogen pump was developed which permitted a reduction in tank weight that more than offset the weight of the pump. Arnold Bierman and Robert Kohl developed the five-cylinder piston pump, driven by a hydraulic motor, for installation in the wing-tip liquid-hydrogen tank.[29]

Flight experiments with the pump extended into 1959. Three successful flights were made. Although the pump speed and discharge pressure varied, the hydrogen regulator maintained a constant engine speed during operation with hydrogen. All the transitions from JP-4 to hydrogen, burning hydrogen, and transition back to JP-4 were made without incident. The feasibility of using liquid hydrogen in flight had been thoroughly demonstrated.[30]

Flight Propulsion Conference

The Bee project of flying an airplane fueled with hydrogen was part of a broader investigation of advanced engines for airplanes and missiles at the NACA Lewis laboratory. The broader vein was presented at a second research conference held on 21–22 November 1957, with 300 attendees. Hydrogen was the chief fuel discussed. The papers were presented by a series of eight panels, five of which were on air-breathing engines. The other three were on rockets (p. 91). Edgar M. Cortright, J. Howard Childs, DeMarquis D. Wyatt, and David S. Gabriel led, describing the air-breathing engine concepts. They pictured military planning as being at a critical stage. The choice of deterrent weapons included the manned bomber, unmanned missile, glide bomber utilizing aerodynamic lift, intercontinental ballistic missile, and satellite bomber for flight beyond the atmosphere. Development of each was expensive and time consuming; the purpose of the first five panels of the conference was to present "an appraisal of the ultimate performance capabilities of aircraft and missiles powered by air-breathing engines"—range, speed, weight, and payload were used as criteria of merit. Flight at very high speed heats aircraft surfaces and requires cooling for sustained flights. Cortright's panel found that only liquefied methane and hydrogen had significant cooling capacity at flight speeds above Mach 5. Hydrogen was the best

fuel for cooling, primarily because it was thermally stable and useful up to the maximum allowable temperatures of the vehicle surfaces.[31]

Fuel heating value was also examined and not surprisingly, the panel singled out the superiority of hydrogen, noting that it was 70 percent better than diborane. Hydrogen's high heating value, combined with its greatly superior cooling capacity, made it extremely interesting as a fuel for long-range hypersonic flight.

The first panel noted the disadvantages of hydrogen's low density—a problem considered by a later panel. Also noted was possible dissociation loss that might limit the realization of full heating value of the fuels considered. These and other considerations provided the basis for detailed discussions of two applications: a manned bomber flying at a speed of Mach 4, to be powered by a new engine; and an unmanned ramjet missile—with all surfaces glowing red hot from air friction at its flight speed of Mach 7—cooled and fueled by hydrogen.

Air-Breathing Engines for High-Speed Flight

After panel discussions of inlets, exits, and cooling, an engine panel headed by H. M. Henneberry analyzed four types of engines for the Mach 4 manned mission and two types of ramjet for the Mach 7 unmanned missile.* The Mach 4 engines were: turbojet, fuel-rich turbofan, hydrogen expansion, and air-turborocket. All four had common elements of air inlet, fan or compressor for increasing the pressure of the incoming air, afterburner where additional fuel was burned, and nozzle. The fan or compressor was driven by a gas turbine, but the turbine and its driving gas differed among the four engines. In the turbojet the driving gas was primarily air, in the fuel-rich turbofan and air turborocket the gas was hydrogen rich, and for the hydrogen-expansion engine the gas was all hydrogen.

Of the four engines, the hydrogen-expansion type is of particular interest because it was under development in a super-secret Air Force project to be discussed later. The hydrogen-expansion engine described by Henneberry had a complex flow system which will be described with the aid of figure 23. Air entering the engine was compressed by a two-stage fan driven, through suitable gearing, by a high-speed turbine. A small amount of air was directed to the primary combustor; the main stream flowed directly to the afterburner. The liquid hydrogen was raised to a high pressure by a pump and served as a coolant for various purposes (such as cooling hot vehicle surfaces) prior to entering the engine. The heat absorbed during these cooling functions converted the hydrogen to a gas. In the engine, the hydrogen flow was split, with one part flowing directly to the afterburner. The other part flowed through a heat exchanger where its temperature was increased substantially. The hot hydrogen was used to drive a 3-stage turbine which, in turn, powered the fan for compressing the air. After leaving the turbine the hydrogen entered the primary combustor where it burned hydrogen-rich with air. The hot, hydrogen-rich combustion gas entered the other side of the heat exchanger where it provided the heat for the separate flow of hydrogen gas

*With Henneberry on the engine panel were A. V. Zimmerman, J. F. Dugan, W. B. Schram, R. Breitwieser, and J. H. Povolny.

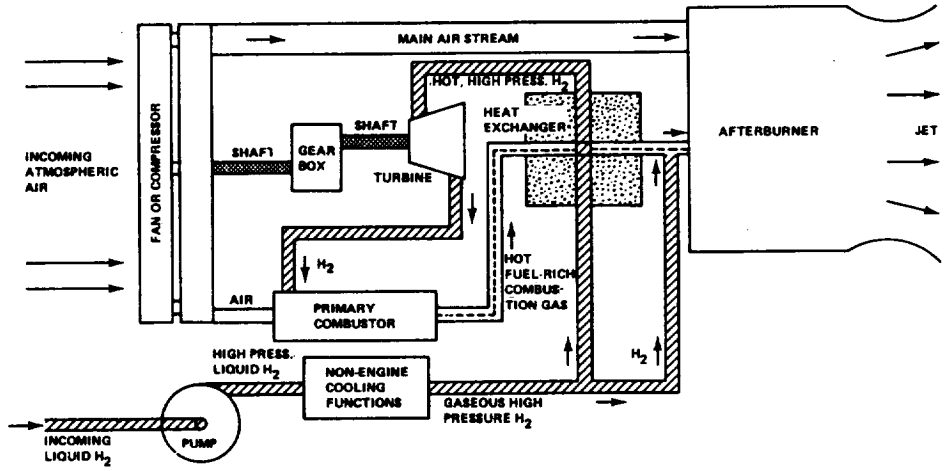

Fig. 23. Schematic of hydrogen expansion engine as described by Henneberry at NACA 1957 Flight Propulsion Conference, 21–22 Nov. 1957.

for the turbine previously mentioned. After leaving the heat exchanger, the hydrogen-rich combustion gas flowed to the afterburner where it and the other part of the hydrogen flow burned to completion, after which the hot gases expanded through the nozzle to provide thrust. Henneberry and his panelists estimated the weight of the hydrogen-expansion engine to be 10 percent heavier than a turbojet, and to have many difficult development problems.*

The turborocket, being pushed by W. C. House of Aerojet-General Corporation, used a small rocket to provide the hot gases for driving a turbine, with the turbine driving the air compressor or fan. The rocket used either a monopropellant or bipropellants—the latter being fuel-rich with additional burning in the afterburner, as in the other engines. The panel described a turborocket using liquid hydrogen as the fuel. After being compressed, part of the incoming air was diverted through a heat exchanger, chilled on its other side by liquid hydrogen. The air was liquefied and pumped at a high pressure to the rocket chamber. The main air-stream flowed directly to the afterburner. Liquid hydrogen, after serving to liquefy the air in the heat exchanger, went directly to the rocket chamber where it mixed and burned fuel-rich with the air. The combustion products drove a turbine (which drove the air fan or compressor). After leaving the turbine, the hydrogen-rich gas flowed to the afterburner where it mixed and burned in the main air-stream. A potential problem in this type of engine was icing from moisture in the incoming air.

*As will be discussed later, Pratt & Whitney built a hydrogen-expander engine and tested it for the first time two months before the NACA conference. The engine development was part of a highly secret Air Force project, and it is very doubtful that the Henneberry panel was aware of it. Another, somewhat similar, type of cycle—the Rex engine—was known to the Lewis laboratory and the Henneberry panel may have drawn on this knowledge. Interview with A. V. Zimmerman, Roger Luidens, and Richard Weber, NASA Lewis Research Center, 30 May 1974.

After comparing the four types of engines, the Henneberry panel concluded that the turbojet was the simplest, would require the least development, and was adaptable to a wide variety of fuels.

Of the two ramjets considered by the Henneberry panel, one was described as conventional, the other fuel-rich. In the former, enough fuel was provided for complete combustion with the oxygen available, while the latter used an excess of fuel. The excess fuel helped to offset decrease in thrust at speeds above Mach 10. The panelists found that hydrogen was superior to diborane and methane for cooling and for performance at high supersonic speeds. They concluded that a fuel-rich ramjet using liquid hydrogen could extend the usefulness of air-breathing engines to speeds up to Mach 18.

Mach 4 Configurations and Missions

Another panel at the NACA 1957 conference on propulsion, headed by Roger W. Luidens, bridged the papers on propulsion with an analysis of the range capabilities of airplanes using the advanced propulsion concepts; it was followed by another panel led by S. C. Himmel that tied all the previous discussions of air-breathing engines, airplanes, and missiles together.* One mission selected for discussion was a speed of Mach 4, altitude of 30 500 meters, a payload of 4500 kilograms, with airplanes using turbojet engines. When designed for hydrogen, the airplane was 91 meters long and had a gross mass of 136 000 kilograms of which about 1/3 was hydrogen. The airplane using JP-4 fuel was half as long, but had a mass 40 percent greater than the hydrogen configuration, with the JP-4 making up 60 percent of the mass. The hydrogen-fueled airplane had a range of just over 5000 kilometers compared to 3050 for the JP-4 airplane (fig. 24). While the hydrogen airplane had the greater range, it was short of the goal of 10 200 kilometers. Use of an air-turborocket increased the range 13 percent, but this was not enough to warrant the cost and time of development. Even with additional engine improvements and by using advanced airframe design, the range of the hydrogen-fueled airplane could be increased to only 7600 kilometers, still short of the goal.

The airplane designs using turbojets were outclassed by a hydrogen-fueled ramjet missile. With a mass of 17 400 kilograms and boosted to its cruising speed, it carried the same payload (4500 kg) at Mach 7 for a distance of 16 700 kilometers. Liquid methane and diborane were both inferior to liquid hydrogen.

The November 1957 propulsion conference at NACA-Lewis proved to be the climax of efforts to promote air-breathing hydrogen-fueled engines as competitors to rocket-powered intercontinental ballistic missiles. Strangely enough, the rich amount of experimental data on hydrogen from Lewis ground and flight experiments was not apparent to members of the audience. What came across strongly from the papers were concepts and trends of what the future could be like with hydrogen in advanced turbojet and ramjet engines. These potentials, however, came too late to catch up with

*With Luidens were J. H. Disher, Murray Dryer, and T. W. Reynolds; with Himmel were E. W. Conrad, R. J. Weber, R. R. Ziemer, and W. E. Scull.

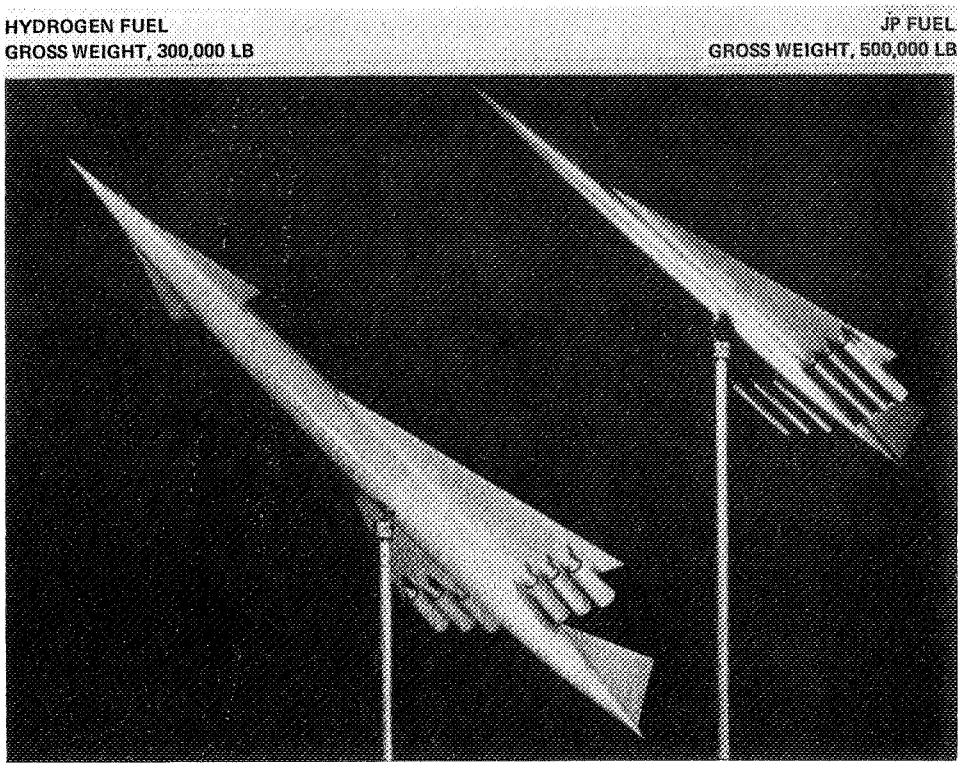

Fig. 24. The effect of fuel type is shown by these models of high-altitude supersonic aircraft. The gross weight of the larger, hydrogen-fueled aircraft (left model) is only 60 percent of that of the smaller, JP-fueled aircraft (model on right). NACA 1957 Flight Propulsion Conference.

ballistic missile development. As a final clincher, Sputnik had ushered in the space age seven weeks earlier and turned attention to space, where the rocket was the undisputed propulsion system.

The many research scientists at the Lewis laboratory who worked on hydrogen as a fuel for high-flying aircraft were completely unaware that a huge and highly secret effort on hydrogen for high-altitude flight had been started in the Air Force the previous year. That work was managed by Col. Norman C. Appold, who attended the NACA conference. The Air Force project will be described in a later chapter.

Summary

During the period 1954–1957, the NACA-Lewis Flight Propulsion Laboratory at Cleveland investigated liquid hydrogen as a fuel for high-altitude aircraft and missiles. The experiments began in 1954 with an investigation of low-pressure combustion in a single turbojet combustor, extended to other components (tanks, pumps, heat exchangers, controls) and complete turbojet engine systems, and culminated in the first (and only) flight experiments. Among the many contributions:

(1) Gaseous hydrogen burns well at low pressures in a turbojet combustor.

(2) Promotion of hydrogen as a turbojet fuel; especially the concept that high-altitude, low-speed flight using turbojet engines demands efficient combustion at low pressure, best provided by hydrogen; and, at the same time, aircraft configurations for that flight regime favor large-volume aircraft which alleviates the disadvantage of hydrogen's low density.

(3) Lightweight, low-loss liquid hydrogen tanks are feasible.

(4) Liquid hydrogen can be pumped satisfactorily for turbojet engine conditions.

(5) Hydrogen requires less combustion volume than hydrocarbons, making possible shorter and lighter engines.

(6) A complete turbojet engine for subsonic flight can be operated with hydrogen at higher altitudes and with less fuel consumption (mass basis) than the same engine using hydrocarbon fuels.

(7) Existing turbojet engines can be easily adapted to use hydrogen.

(8) Flight demonstrations that liquid hydrogen can be handled safely in ground operations and in flight.

(9) Liquid hydrogen is an excellent heat-sink for very high-speed flight where air friction heats the vehicle surfaces.

(10) Turbojets using hydrogen give good performance at flight speeds of Mach 4 and ramjets for flight speeds of Mach 7, with much higher speeds feasible with the latter.

All these advantages made hydrogen appear to be the fuel of the future for advanced air-breathing engines; but, in fact, its prospects were already being tested, as we will see.